PS Geological Controls of Regional Petroleum Gas Hydrate Occurrence, Beaufort-Mackenzie Basin, Canada*

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Abstract

Methane hydrate is a potentially important strategic petroleum resource globally. The analysis of 250 digital well logs from petroleum exploration wells in the Beaufort-Mackenzie Basin (BMB) illustrate and provide new insight into the geological controls of methane hydrate occurrence and resource potential in the BMB. Analyses of the spatial distribution of the inferred methane gas hydrate occurrence in comparison to the conventional petroleum system elements indicates that conventional petroleum system elements exert a fundamental control on the occurrence of methane hydrate accumulations in the basin. The inferred high concentration gas hydrates are restricted to the central part of the study area, where combination of a favorable thermal regime, including specific aspects of the Pliocene and younger surface temperature history, the presence of a permeable network and abundant supply of thermogenic gases from hydrocarbon kitchens, provides favorable conditions for forming large accumulations of methane gas hydrate. Commonly high temperature anomalies and the presence of fault/fracture systems are closely associated with gas hydrate occurrence with high methane saturations, indicating that deep fluid flow systems are involved in the formation of gas hydrate accumulations. High saturation gas hydrate accumulations are less common in northeastern part of the study area, at least in part, if not primarily, because of the lack of effective migration network connecting the thermogenic gas kitchens and gas hydrate stability zone. Absence of gas hydrate deposits in the west Beaufort Sea is primarily due to an unfavorable thermal regime for formation of thick gas hydrate stability zone.

This paper suggests that conventional petroleum systems exert a fundamental control on the distribution and richness of inferred gas hydrates. Our results are consistent with recent model studies that suggest that major BMB gas hydrate accumulations formed as a

result of the transformation of previously trapped conventional gas in response to surface temperature forcing since Pliocene time. Together these results suggest both that:

- understanding the conventional petroleum system is a key to understanding gas hydrate resource distributions and
- that most high saturation gas hydrate accumulations are elements of the conventional petroleum system that were transformed in-place in response to surface temperature forcing history.

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Geological controls of regional petroleum gas hydrate occurrence, Beaufort-Mackenzie Basin, Canada

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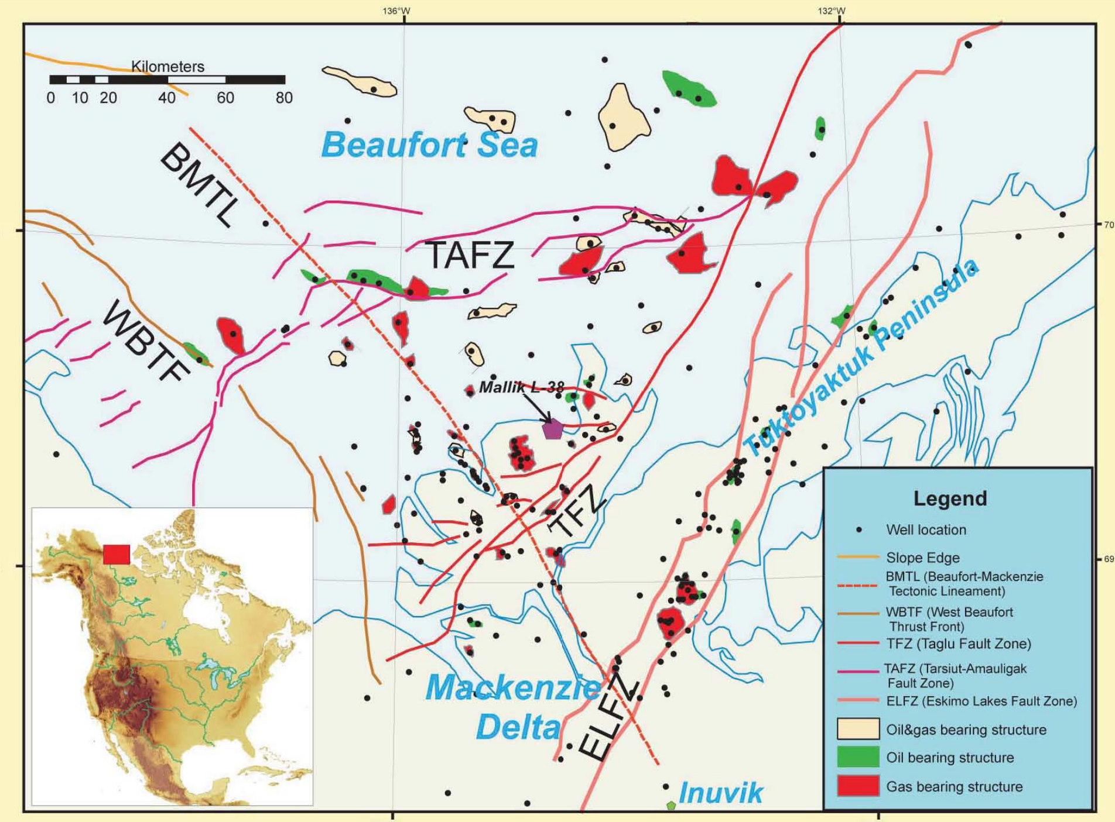
Abstract

Petroleum gas hydrates (GHs) are a potential petroleum resource of strategic importance for future global natural gas supply. Sub-permafrost gas hydrate bearing strata are widespread in the Beaufort-Mackenzie Basin (BMB). Initial direct evidence for highly concentrated GHs came from core samples in the Mallik 2L-38 well and a short production test in Mallik 5L-38 well. Many additional GH accumulations were inferred subsequently using geophysical well log data in conventional petroleum wells. The stable carbon isotopic composition of GHs in the Mallik 2L-38 and 5L-38 wells indicate that the methane has thermogenic origin. The Beaufort-Mackenzie Basin is also a proven conventional petroleum province with a large prospective conventional natural gas and crude oil resource. Concentrated GHs are often co-located geographically with conventional petroleum accumulations, suggesting that shared geological controls affect both the conventional and GH accumulations. Digital well logs from 250 petroleum exploration wells in the BMB were examined to better understand the geological controls on regional GH occurrence and resource potential. The spatial distribution of inferred GH relative to petroleum system elements suggests a fundamental petroleum system control on the GH occurrence in this basin. Concentrated GHs are restricted commonly to the central study area, where, a favourable thermal regime, a permeable migration network and an abundant thermogenic gas supply from hydrocarbon generation kitchens, provides a favourable combination of conditions for large GH accumulations. Local high temperature anomalies and fault/fracture zones are commonly found closely associated with concentrated GH occurrences, suggesting the involvement of deep fluid flow for the rich GH accumulation. Concentrated GH accumulations are less common in the north-eastern study area probably because it lacks of effective migration network that connects the thermogenic gas in generation kitchens to the GH stability zone. Absence of structure I GH deposits in the west Beaufort Sea is attributed to an unfavourable thermal regime that precludes the formation of a thick GH stability zone even where sufficient thermogenic gas supplies and a permeable migration network are present.



(Fault pattern is based on Lane and Dietrich, 1995)

Figure 1: A map showing the study area, exploration results and regional structural features of the BMB. More than 260 wells found fifty-four significant conventional oil and gas discoveries. Structurally, the southwest Beaufort Sea is a foreland basin, where thrust faults and compressional folds are common. The eastern part is a rifted passive margin, where listric faults and rollover folds dominate. Along the southeast basin margin, thin Tertiary strata were deposited on a Jurassic-Cretaceous rift system. Between the contractional and extensional domains, there is a transitional zone characterized by transpressional structures.

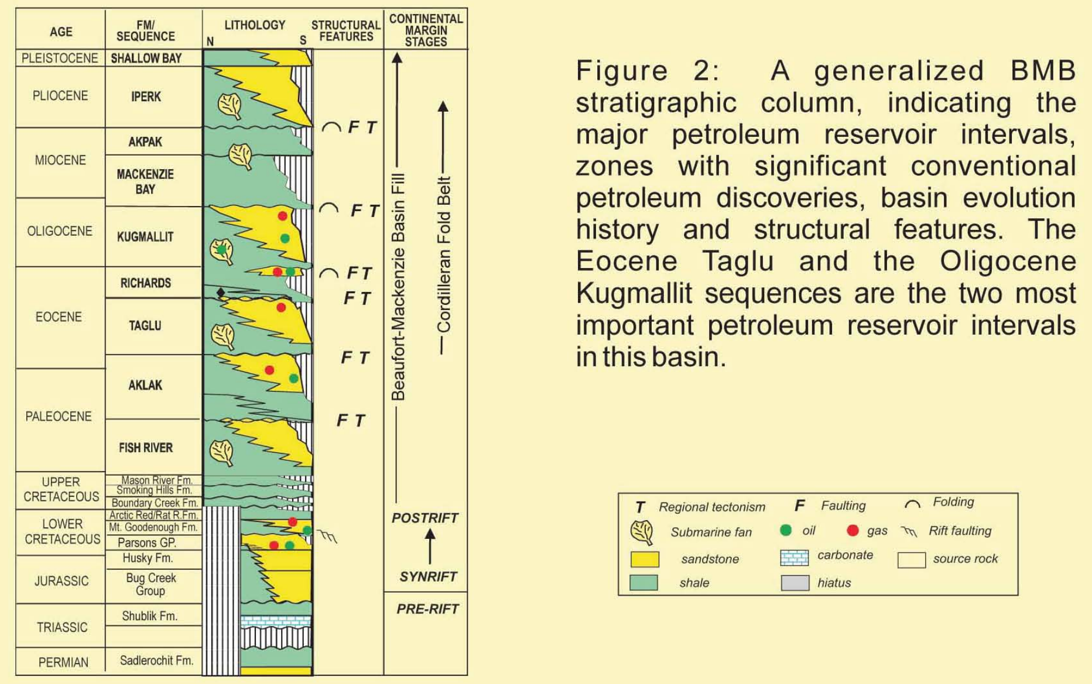


Figure 2: A generalized BMB stratigraphic column, indicating the major petroleum reservoir intervals, zones with significant conventional petroleum discoveries, basin evolution history and structural features. The Eocene Taglu and the Oligocene Kugmallit sequences are the two most important petroleum reservoir intervals in this basin.

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Gas hydrate Stability Zone

Given a hydrostatic pressure gradient in the uppermost 2 km, the GH stability zone (GHSZ) is controlled primarily by the thickness of relict terrestrial permafrost formed during the last glacial sea level lowstand and the variation of subsurface temperature field. Other factors, such as formation water salinity, can shift the GHSZ base, with magnitude comparable to the uncertainty in the geothermal gradient estimate. Permafrost thickness varies between <50 meters in the western Beaufort Sea to >740 meters in the central Mackenzie Delta and eastern Beaufort Sea (Issler et al. in press). Previous work suggests that near surface processes, such the glacial ice cover variations, lithology, and surface water flow control permafrost thickness (Allen et al. 1988). Recent work suggests that permafrost thickness variations also are affected by subsurface temperature field (Chen et al. 2008).

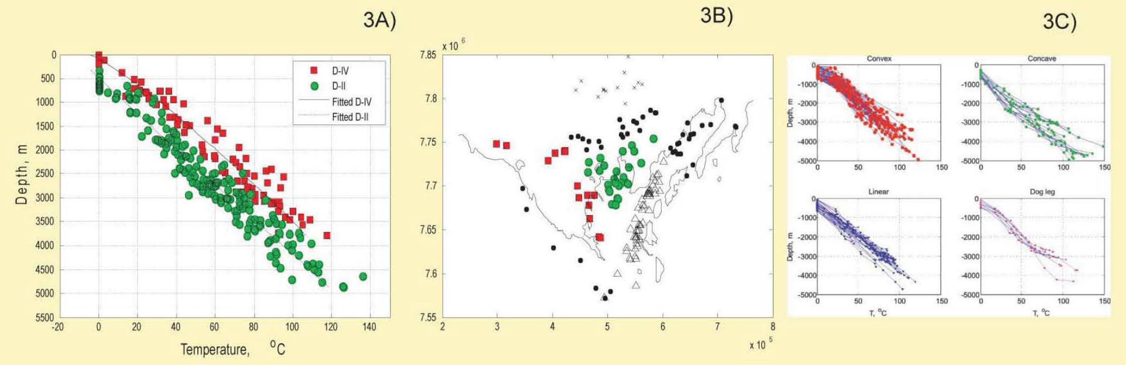


Figure 3: Comparison of temperature profiles between the western Beaufort Sea, which has been significantly uplifted and eroded, with the central Mackenzie Delta, where subsidence and sedimentation preserve Tertiary succession (Figure 3A and 3B). An average 20 °C temperature difference is observed between these two areas (Figure 3A). Tectonic setting influences basin thermal structure, resulting in characteristic temperature profiles in each of the tectonic domains (Figure 3C).

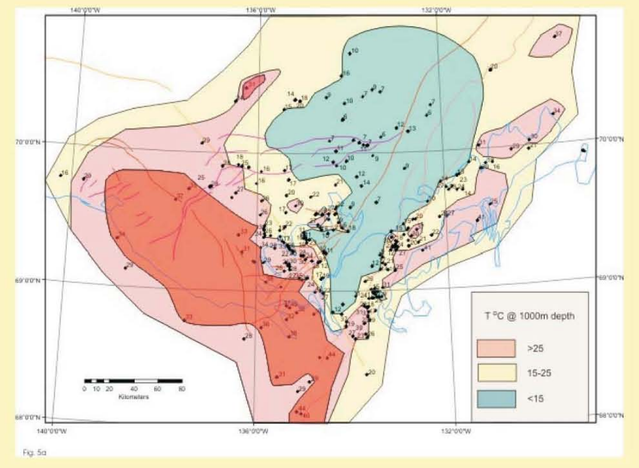


Figure 4: A map showing temperature at 1 km depth. Elevated temperatures occur in the southwest, where temperatures are >25 °C and could be up to 40 °C. In the central delta and northeast shelf temperatures are suppressed, below 15 °C and possibly as low as 6 °C. A similar pattern of temperatures suppression is also observed to 3 km depth (Chen et al., 2008).

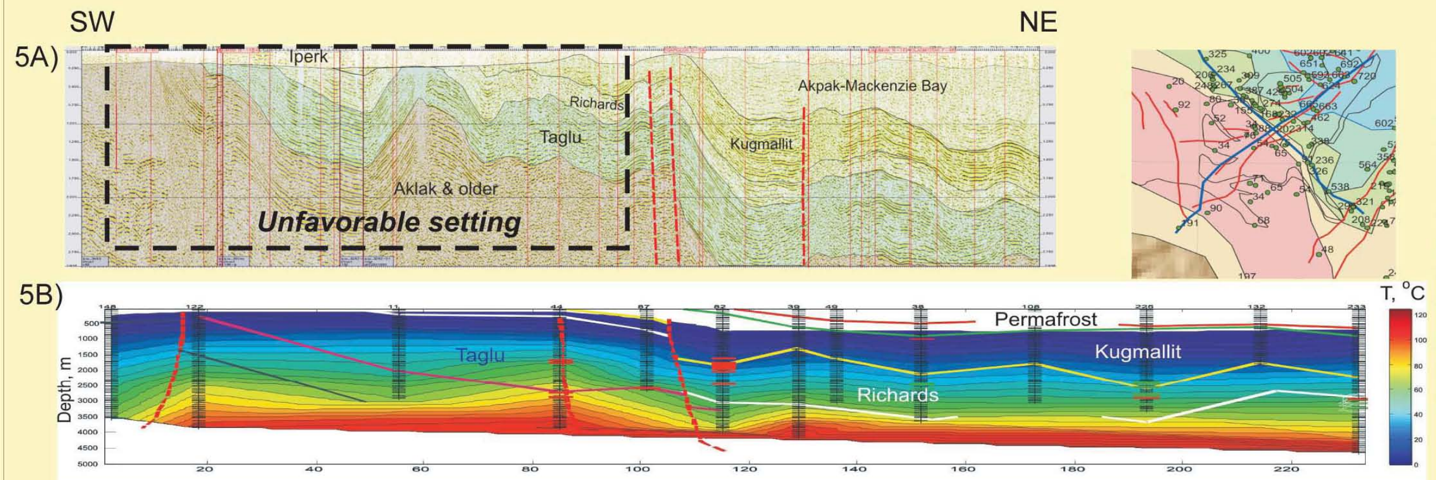


Figure 5A: A NE-SW regional seismic profile showing the stratigraphic succession and structural characteristics of the south-western and central delta (see location index map on the left). Figure 5B: A temperature profile crossing Figure 5A showing accompanying subsurface temperature and permafrost thickness variations. Thin permafrost occurs in the southwest where extensive deformation has also removed a thick Late Tertiary strata.

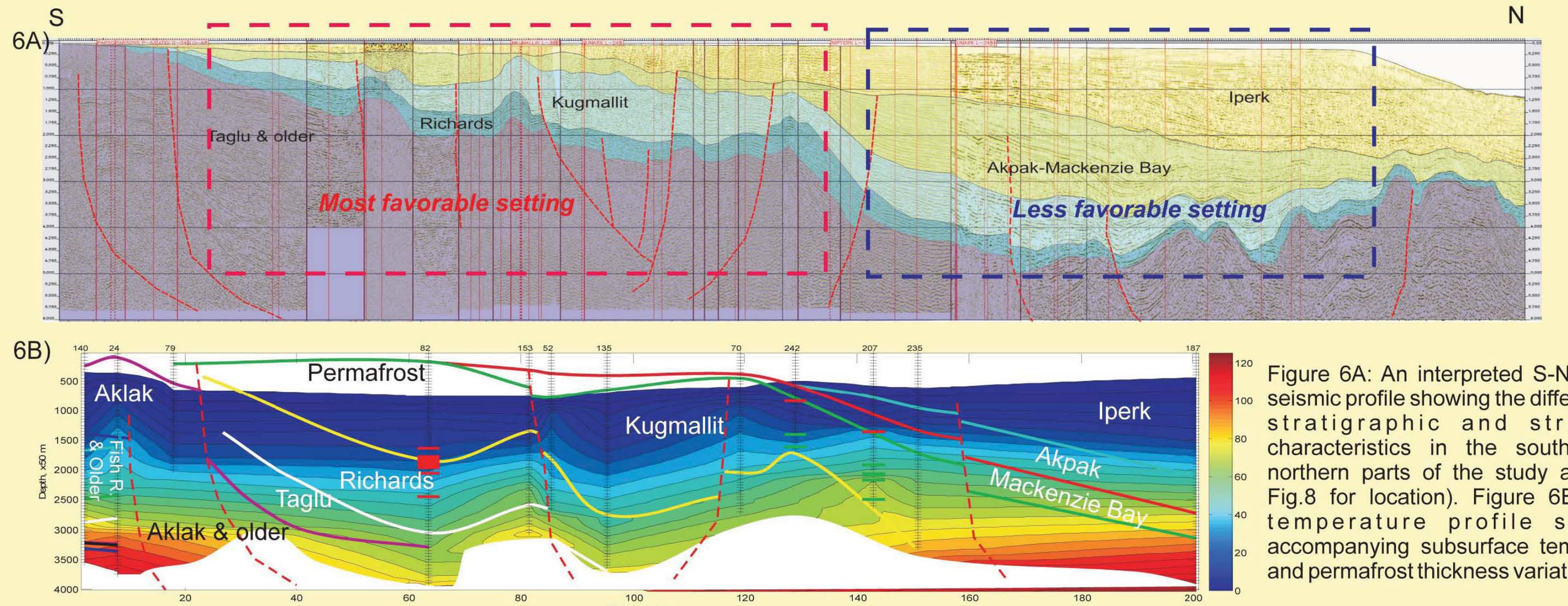


Figure 6A: An interpreted S-N regional seismic profile showing the differences in stratigraphic and structural characteristics in the southern and northern parts of the study area (see Fig.8 for location). Figure 6B: A S-N temperature profile showing accompanying subsurface temperature and permafrost thickness variations.

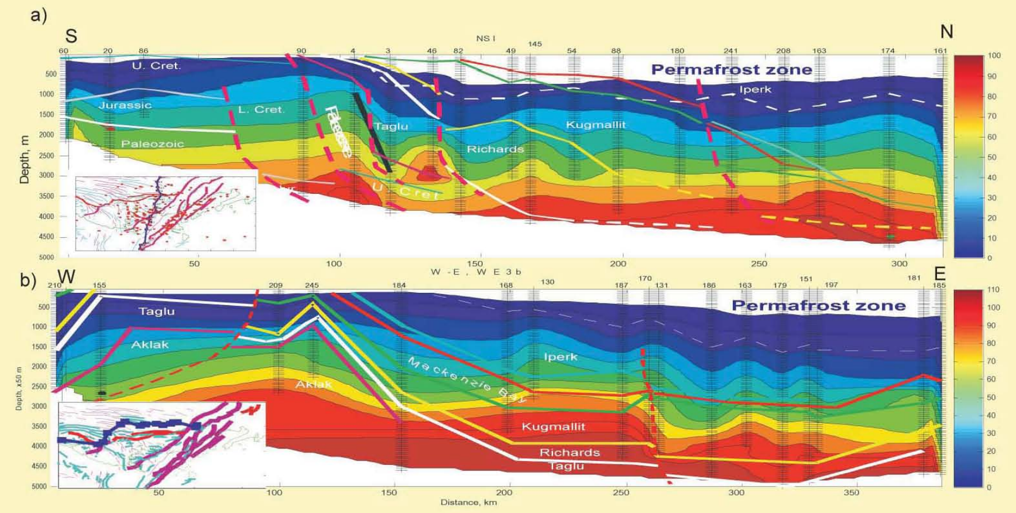


Figure 7a and b. S-N and W-E subsurface temperature profiles illustrating the elevated and suppressed temperature isotherms, in the south and west, and north and east, respectively. Permafrost thickness variation following the temperature field: permafrost is generally thin where temperatures are elevated and thick where temperatures are suppressed.

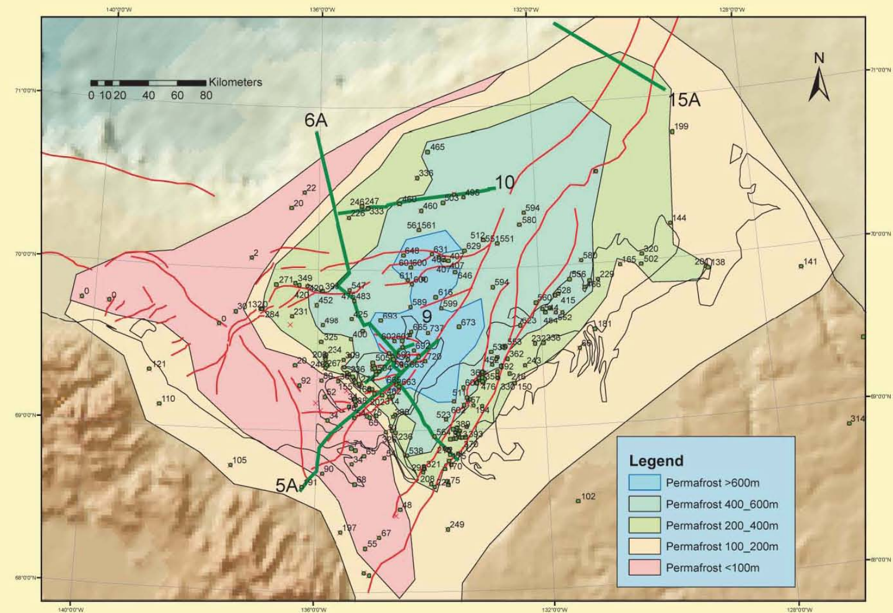


Figure 8: A permafrost thickness map constrained by petroleum exploration well and seismic check-shot velocity data that shows the geographic variations of permafrost thickness and its relationship to regional geological features. The regional seismic lines are in Figure 5A, 6A, 9, 10 and 15A.

Gas hydrate occurrence and petroleum system controls

Inferred concentrated sub-permafrost GHs occur predominantly in the area between the extensional and contractional tectonic domains, specifically in the eastern Richards Island area, where permafrost thickness is >300 m. Concentrated GHs are inferred less common farther north and in the southeast rifted margin. No structure I GH is inferred to occur in the western Beaufort Sea, where permafrost thickness is <100m. The rich sub-permafrost GH has western and south-western geographic limits along the Beaufort - Mackenzie tectonic lineament (BMTL), which is attributed to unfavourable thermal conditions to the west. To the north a recent marine GHSZ may occur where water depths approach 300 meters and relict permafrost is absent. In the Mallik L-38 prospect, structure I (methane-only) GH predominates with minor Structure II (heavier hydrocarbon) GH. Well logs in some wells, such as Adgo, Niglintgack and Kumak prospects indicate potential occurrences of Structure II+H GHs. All of these wells occur along the BMTL and all are geographically co-located with underlying conventional petroleum accumulations.

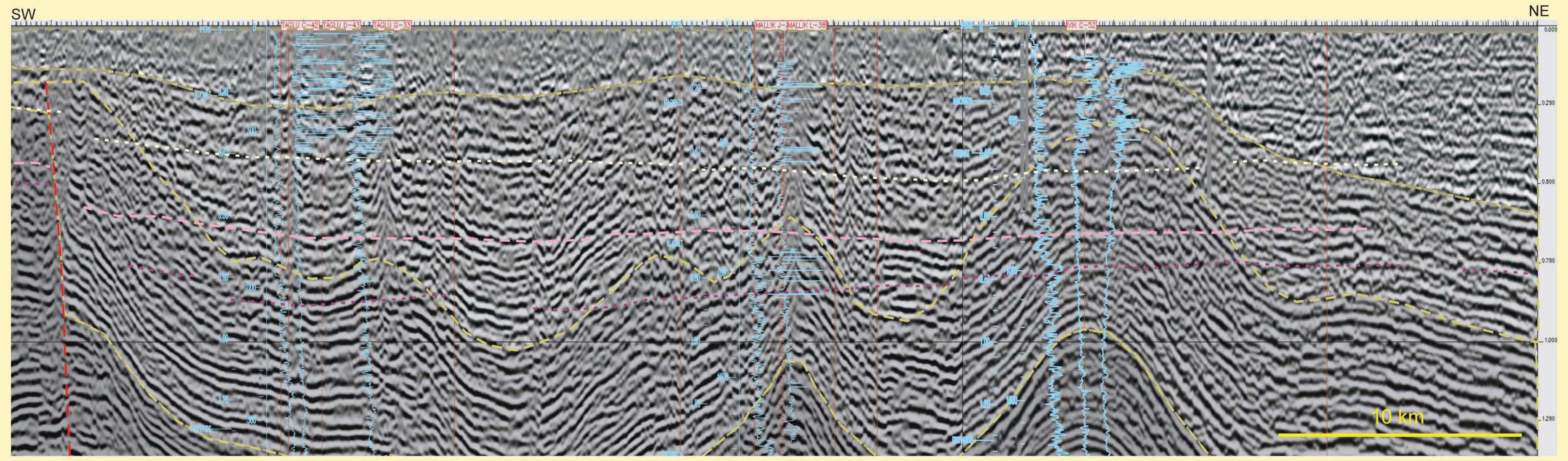


Figure 9: A NE-SW seismic line, crossing the Mallik GH field and adjacent area, with well logs superimposed and indicating the interpreted permafrost base (light yellow dashed line), GH occurrence top and base (light and dark brown dashed lines). Many of the inferred rich GH accumulations are located where a strongly faulted and folded Eocene-

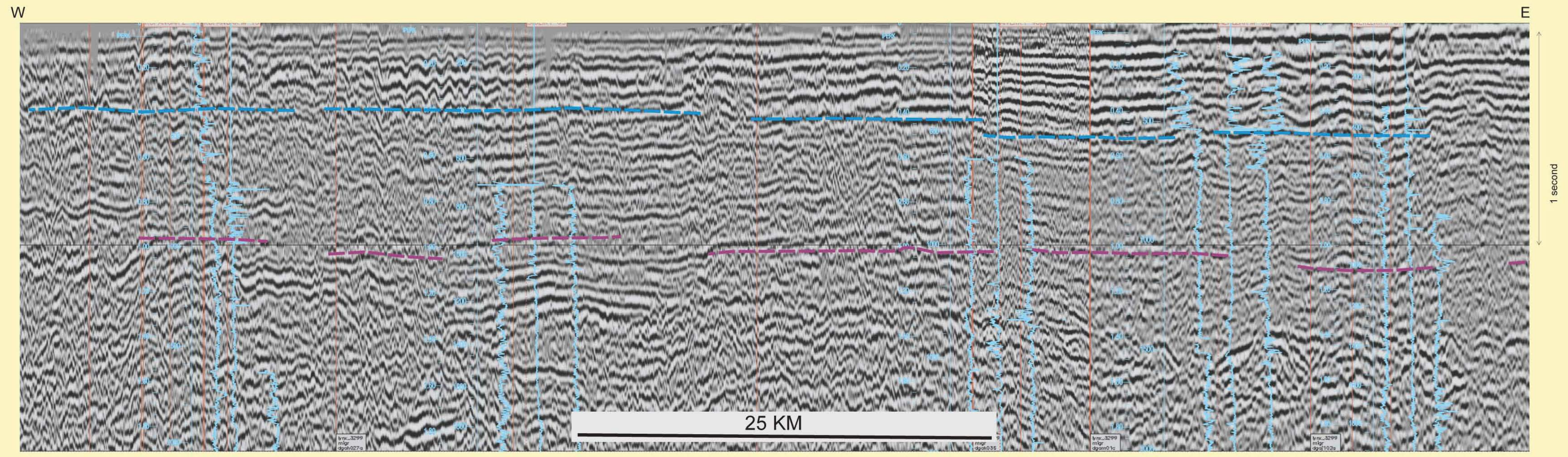


Figure 10: A W-E seismic profile, crossing the Kopanoar M-13 and Nerlerk J-67 wells, with well logs superimposed, and interpreted permafrost (dark blue) and base of GH (brown dashed line). Most of faults occur below the Pliocene Iperk Sequence and rich GHs are less common here due to a lack of connection between porous reservoir in the GHSZ zone and the thermogenic petroleum system. In Iperk Sequence only a few concentrated GH accumulations are inferred to occur where upward flow of fluids originating in the deep succession have migrated into the GHSZ along faults and fracture zones associated with structural culminations that connect the gas generation kitchens to reservoirs in the GHSZ. This is particularly common in the north and east, where the undeformed Iperk Sequence is generally >2500 m thick.

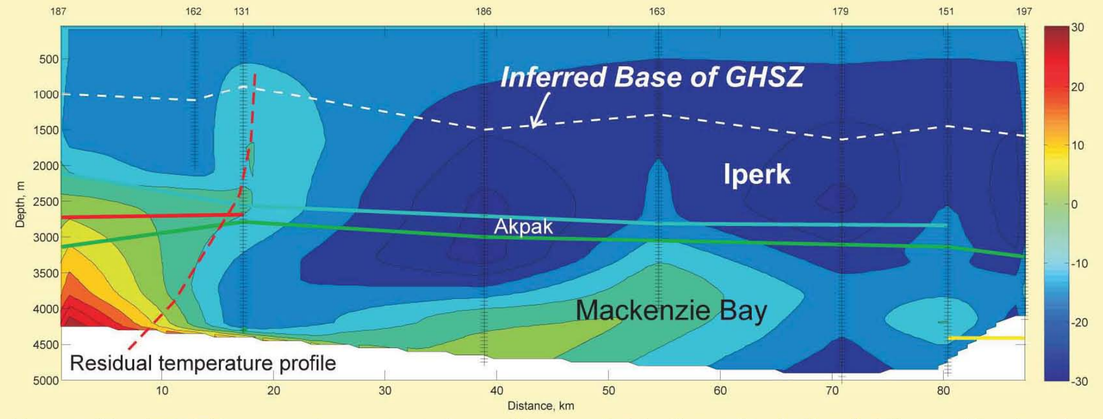


Figure 11: A W-E temperature anomaly profile parallel to the seismic line in Figure 10, showing the relationship among local temperature anomalies, inferred GHs accumulations and conventional petroleum discoveries. Local high temperature anomalies indicate upward migration of deep fluids that outline oil & gas migration fairways which link deep petroleum "kitchens" to the shallow stratigraphic succession. The status of the exploration wells are: 187, D&A; 162, D&A; 131, (Kopanoar M-13) oil & gas discovery; 186, D&A; 163 (Koakoak O-22) oil & gas discovery; 179, D&A; 151, (Nerlerk J-67) oil discovery; 197, D&A.

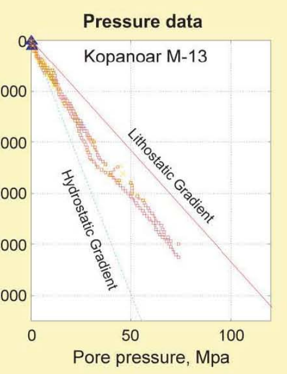


Figure 12: The high pore pressure in most of the interval profile penetrated by the Kopanoar M-13 well, inferred from mud weight.

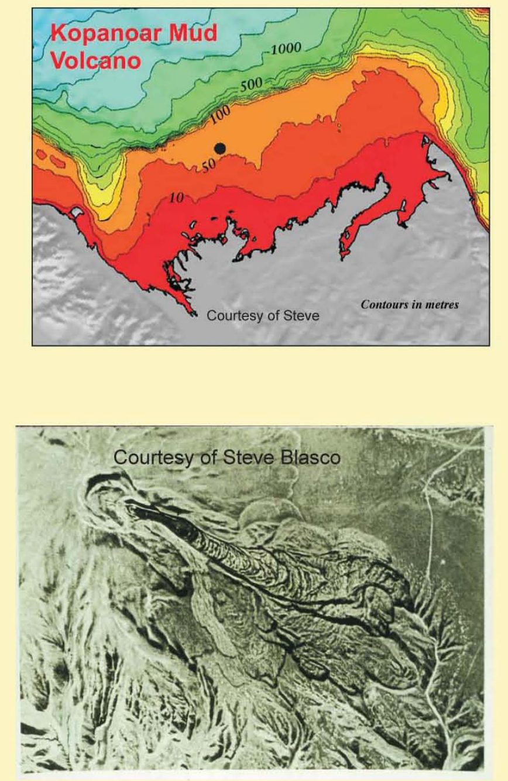


Figure 13: Sea bed expression of an active mud volcano on top of the Kopanoar structure. The observed bottom hole temperature and mud weight in the Kopanoar wells are consistent with the sea-bed expression, suggesting an active mud volcano system driven by overpressure in the deeper stratigraphic intervals. This illustrates how deep fluid flow results in material migration upward through faults and fracture zones over structural culminations.

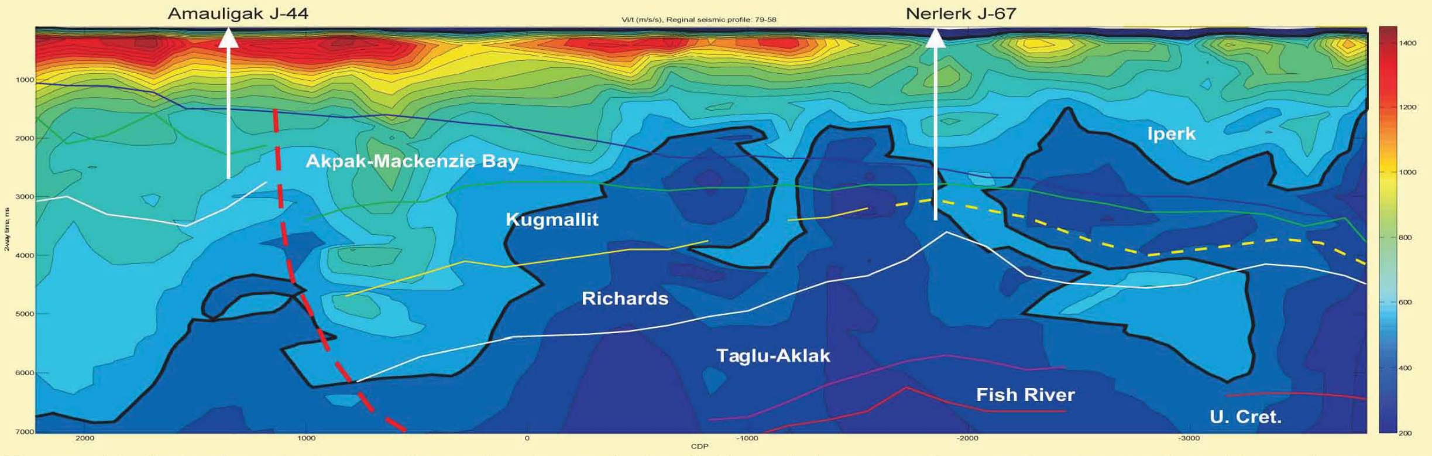


Figure 14: Seismic velocity gradient showing velocity field variation superimposed onto stratigraphic and structure interpretations on a profile that crosses the Amauligak J-44 and Nerlerk J-67 well locations. Vertical or sub-vertical low velocity zones may indicate the paths for upward gas and fluid migration. Velocity gradient horizontal variations in the shallow section are inferred to indicate basin-ward thinning of the relict permafrost.

Figure 15: Seismically inferred GH and conventional natural gas accumulations in the "Hinge Line" play region. A) GSC seismic Line fgp87-1; B) Seismic interval velocity anomalies indicating both possible GH and free gas accumulations; and C) a petroleum system play model of petroleum occurrences.

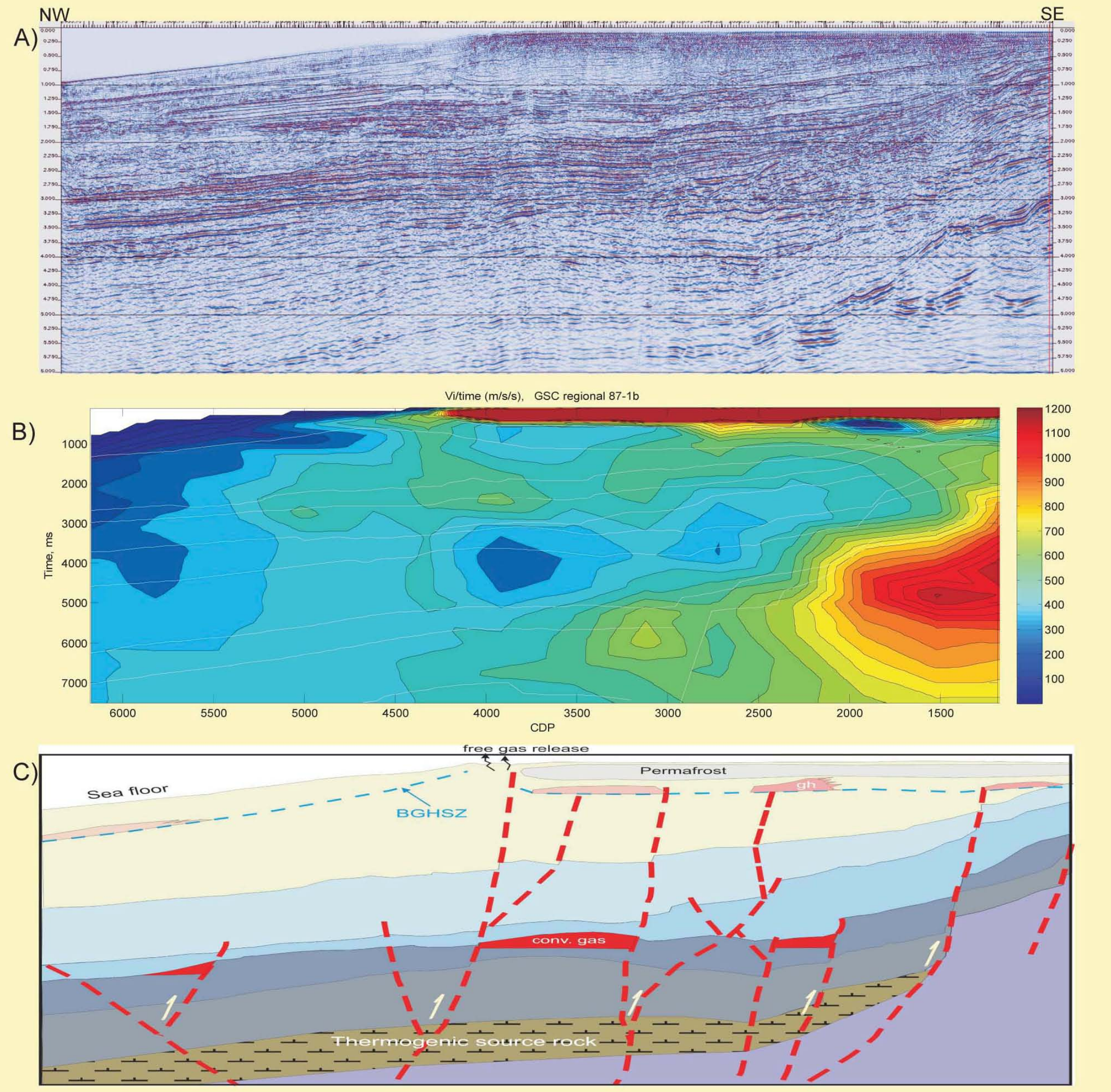
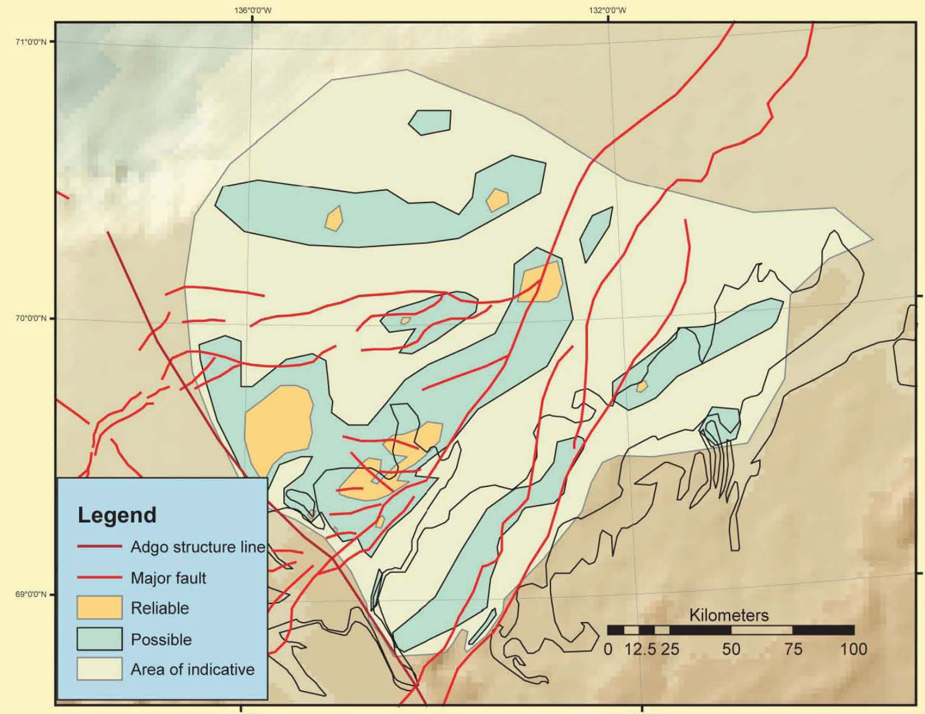


Figure 16: A map showing well log indications for GH occurrence in the BMB. The inferred GH occurrences are grouped into three quality categories (reliable, possible and indicative) based on interpretational confidence. The "reliable" category includes wells where either GHs were recovered or where well log indications suggest concentrated GH accumulations with a gross interval thickness > 10 meters. The "possible" category includes wells with significant log indications for moderate concentrations of GH. The third group includes wells with some well log indications for GH, but where the interpretation is uncertain due to well condition and environment. Wells drilled primarily to deeper conventional petroleum targets can exhibit significant formation damage in the GHSZ, resulting in a partial to complete obscuring of near well bore indications of GH occurrences.



Conclusions

A) Observed and inferred concentrated sub-permafrost GHs occur predominantly in the eastern Richards Island area where permafrost thickness is commonly >300 m and where the tectonic setting is a transition between cordilleran compression and passive margin extension. No structure I GH is inferred to occur in the western Beaufort Sea where an elevated temperature contributes to an unfavourable thermal environment for GHSZ.

B) Rich GH accumulations are often accompanied by local positive temperature anomalies that occur in areas with a moderate tectonic deformation intensity, where a favourable thermal environment preserves a thick GHSZ, and active faults provide effective conduits for the migration of thermogenic gas into reservoirs currently in the GHSZ.

C) Concentrated GH is less common in north and northeast because the thick, undeformed Pliocene succession acts as an effective barrier that prevents the migration of thermogenic gas into reservoirs in the GHSZ even where permafrost is >400 meters thick. In that region only a few rich GH accumulations are inferred to overlie deep structures where overpressures occur together with faults and fractures that permit thermogenic gas migration upward into the current GHSZ.

D) Geophysical anomalies and deeper petroleum discoveries below the current GHSZ base suggest possible Structure II+H GH occurrences along the Adgo Structure line.